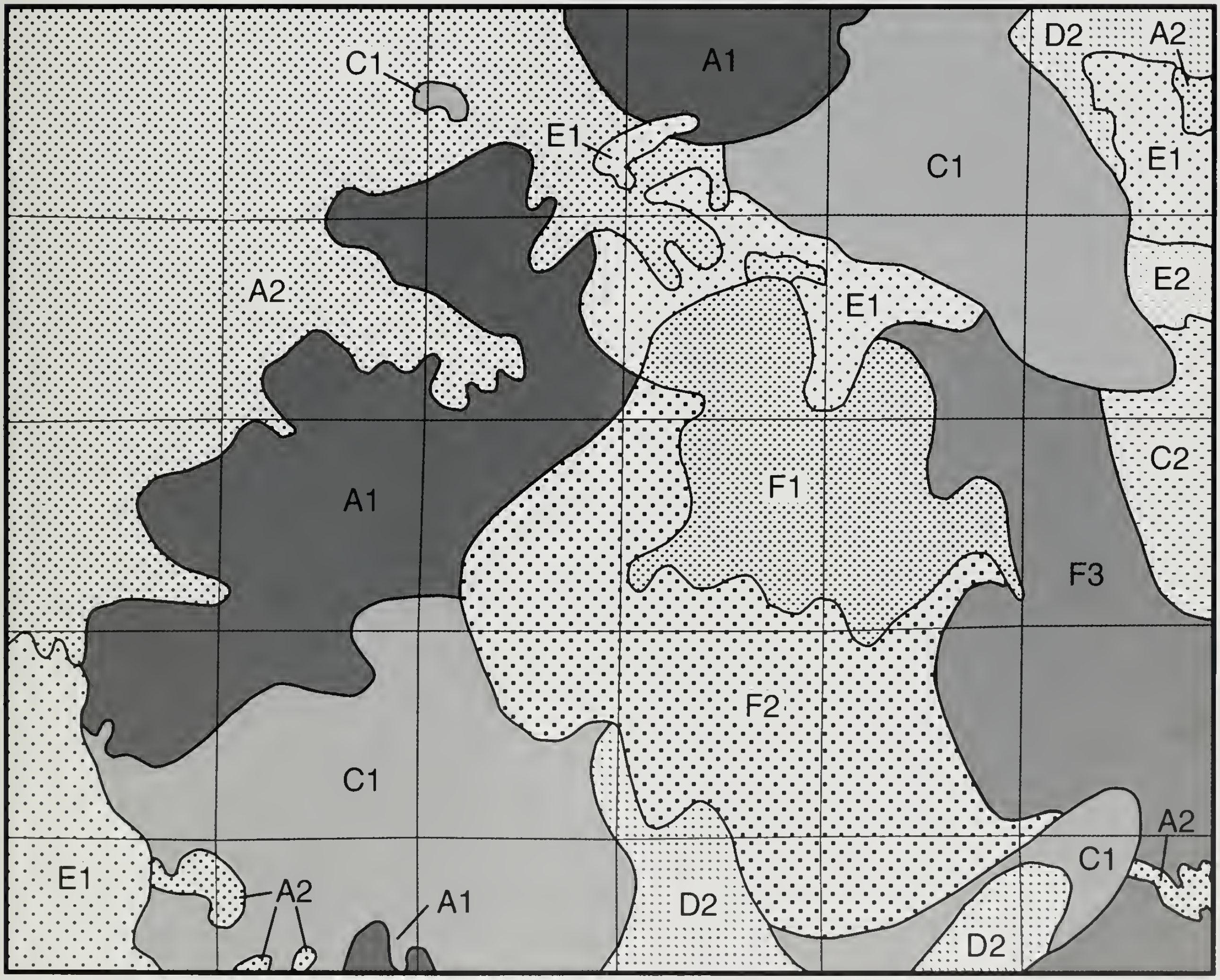
Aquifer Sensitivity Classification for Illinois Using Depth to Uppermost Aquifer Material and Aquifer Thickness

Richard C. Berg



Circular 560 **2001**

George H. Ryan, Governor

Department of Natural Resources
Brent Manning, Director

ILLINOIS STATE GEOLOGICAL SURVEY
William W. Shilts, Chief

ACKNOWLEDGMENTS

I wish to acknowledge reviewers of the report—Don Keefer from the ISGS and Dave Soller of USGS-Reston—for their thoughtful comments; Curt Abert who provided insight on the classificaiton scheme and color and pattern designs for figure 1; and Cheryl Nimz and Mike Knapp for editorial and graphics assistance.

ILLINOIS DEPARTMENT OF NATURAL RESOURCES

ILLINOIS STATE GEOLOGICAL SURVEY 1905

printed by authority of the State of Illinois/2001/900

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INTRODUCTION

The Illinois State Geological Survey (ISGS), since about 1963, has maintained a program specifically designed to geologically map the state for the purpose of delineating aquifers and protecting groundwater resources (Hackett 1963, 1965; Sheaffer et al. 1963). The program grew from the increasing need to portray three-dimensional geologic information in a manner that was directly applicable to hydrogeologic and land-use interpretations (Kempton et al. 1989). The philosophical approach has been to evaluate the contamination potential of aquifers from existing pollution sites and various land-use activities. Contamination may result from many sources, especially the following:

1. disposal of municipal, hazardous, and low-level radioactive wastes;
2. improper handling and storage of hazardous wastes, particularly at commercial and industrial establishments;
3. leaking underground storage tanks and pipe lines containing oil, gasoline, and other chemicals;
4. application of fertilizers and pesticides on agricultural fields and residential lawns;
5. septic systems;
6. sewage sludge, septage, and manure spread on agricultural fields;
7. lagoons and pits holding animal wastes at large animal confinement facilities;
8. accidental spillage of chemicals; and
9. road salt and other deicers.

Aquifers are geologic materials that yield useful quantities of groundwater rapidly to small-diameter wells. These materials include sand and gravel, uncemented sandstone, and fractured limestone and dolomite. Till, silty/clayey lake sediments, wind-blown silt (loess), and non-fractured bedrock (shale, limestone, or dolomite) are not aquifers, even though they may yield small amounts of water to large-diameter residential wells from thin sand seams and fractures.

Aquifers can be sensitive to contamination because their hydrogeologic properties allow wastes to travel rapidly. However, the potential for an aquifer to become contaminated depends on the properties of the earth materials above and below it (Berg et al. 1984a). In general, aquifers at depth have a lower potential for becoming contaminated than do aquifers near or at the land surface.

In compliance with U.S. Environmental Protection Agency (US EPA) terminology, groundwater contamination potential or aquifer susceptibility is defined as "aquifer sensitivity" (US EPA 1993). Aquifer sensitivity is the relative ease with which a contaminant of any kind applied on or near the land surface can migrate to an aquifer. Aquifer sensitivity is a function of the intrinsic characteristics of the geologic materials but is not dependent on land use or contaminant characteristics. "Aquifer vulnerability," however, focuses on the vertical migration of contaminants into the groundwater and is dependent on land-use management practices, contaminant characteristics, and aquifer sensitivity conditions.

Purpose

The purpose of this report is to provide an updated classification of aquifer sensitivity that can be applied to the commonly occurring geologic settings in the state, particularly those with sand and gravel or high-permeability bedrock aquifers within 100 feet of the land surface. This depth is important because studies in Minnesota (Klaseus et al. 1989) and Iowa (Libra et al. 1993) reported a very low incidence of agricultural chemicals in aquifers lying >100 feet below the land surface. Geologic settings are used as surrogates for hydrogeologic settings such that ranges in hydraulic conductivity are assumed for various geologic materials (Table 1), and uniform groundwater gradients are inferred within and between each setting. Measured hydrologic or hydraulic data are not used in this classification. Although numerous factors must be considered for conducting an aquifer sensitivity assessment (US EPA 1993), this classification relies primarily on aquifer type, depth to the uppermost aquifer, and aquifer thickness, all of which can be readily derived from a three-dimensional geological mapping program.

Table 1 Estimated hydraulic conductivity of typical geologic materials in Illinois (Berg et al. 1984a; Battelle Memorial Institute and Hanson Engineers, Inc. 1992; Cartwright and Hensel 1993).

Geologic materials	Hydraulic conductivity (cm/sec)	Comments
Clean sand and gravel	1×10^{-3}	May be highly permeable; good aquifer material
Fine sand and silty sand	1×10^{-5} to 1×10^{-3}	Good aquifer material
Fine-grained glacial sediments	1×10^{-9} to 1×10^{-5}	Includes till and lacustrine sediment; commonly contain gravel/sand lenses; generally non-aquifer material
Silt	1×10^{-6} to 1×10^{-4}	Loess; non-aquifer material
Uncemented sandstone	$>1 \times 10^{-4}$	May be highly permeable; good aquifer material
Cemented sandstone	1×10^{-7} to 1×10^{-4}	Frequently fractured; locally good aquifer material
Fractured shale, limestone, and dolomite	$>1 \times 10^{-4}$ [1]	May have extremely high hydraulic conductivity; good aquifer material
Unfractured shale	1×10^{-11} to 1×10^{-7}	Non-aquifer material
Dense unfractured limestone and dolomite	1×10^{-11} to 1×10^{-8}	Non-aquifer material

[1] Although movement of water through "normal" fractured rock may be $>1 \times 10^{-4}$ cm/sec, recharge and movement of water within karst aquifers are very rapid and often measured in seconds to minutes. Flow is often comparable with the flow rates of surface streams (Frankie et al. 1997). Karst terrains comprise limestone and dolomite rocks that have been dissolved by water resulting in sinkholes, caves, and underground streams.

The new aquifer sensitivity classification draws on aquifer sensitivity rating schemes from numerous published ISGS maps and reports to provide a unified scheme that future mappers can use directly. The new classification also provides a framework that is adaptable to any unusual unforeseen hydrogeologic settings, which is particularly valuable for integrating more hydraulic and hydrologic data with the new scheme and for evaluating enhancements to the sensitivity assessments that these types of data may bring. In total, twenty-four hydrogeologic settings have been delineated in Illinois.

Since the first map of aquifer sensitivity in Illinois was produced (Cartwright and Sherman 1969), there have been new approaches to three-dimensional mapping (primarily from increased computing capabilities and Geographic Information System [GIS] software) as well as an upswing of geologic mapping activity through U.S. Geological Survey (USGS)- and state-funded programs. As a result, numerous statewide, county-scale, and quadrangle-scale aquifer sensitivity maps have been produced as derivative maps from geologic mapping programs (ISGS 1999). The USGS-funded programs include FEDMAP, STATEMAP, and EDMAP, which were designed specifically to produce regional and 1:24,000-scale maps of surficial deposits and bedrock. The recently formed Central Great Lakes Geologic Mapping Coalition (USGS 1999) plans to map at 1:24,000 scale about 1,200 quadrangles in Illinois, Indiana, Ohio, and Michigan over the next 15 years if required appropriations are added to the USGS budget to support the work. The ISGS-funded mapping efforts include the Illinois Geologic Mapping Program (IGMaP) as well as numerous other mapping projects supported by contracts.

As the ISGS geologic mapping program continues to grow and aquifer sensitivity mapping continues to be an integral component, new technologies and methods for determining hydrologic and hydraulic properties of materials will undoubtedly emerge, resulting in new ways to portray aquifer sensitivity. However, for the time being, the most feasible way to present an assessment of aquifer sensitiv-

ity is a classification scheme based on the simplest of parameters that can be relatively easily obtained while conducting a three-dimensional geologic mapping program (e.g, aquifer vs. non-aquifer, aquifer type, depth to uppermost aquifer, and aquifer thickness) Attempts have been made to follow certain conventions for assessing aquifer sensitivity based on these parameters (Berg et al 1984a). However, because of varying objectives of sponsors and because of personal preferences, mapping approaches have been inconsistent (e.g., using different values for aquifer thicknesses and depths to aquifers and even a lack of set colors to indicate various sensitivity classes). This lack of standardization has made it difficult to compare depths to aquifers and delineate aquifer thicknesses on sensitivity maps from one part of the state to another. The classification outlined in this publication presents a consistent framework so that geologists and users, respectively, can map and understand similar geologic settings throughout the state. This type of framework is particularly important in areas where the range of settings is incomplete.

BRIEF HISTORY OF AQUIFER SENSITIVITY MAPPING IN ILLINOIS AND LITERATURE REVIEW

Public Policy, Aquifer Protection, and ISGS Response

Between the mid-1960s and the mid-1980s, increased public awareness of groundwater contamination issues combined with the inability of public officials to evaluate effectively the seriousness of the issue led the US EPA and the Illinois Environmental Protection Agency (IEPA) to develop legislation and rule-making to require a variety of steps to protect groundwater. These new laws and rules prompted the ISGS to provide increased earth-resource–based information. For example, during the early to mid-1970s, the ISGS initiated its Geology for Planning program under contract to the Northeastern Illinois Planning Commission (NIPC), which was responding to provisions of Section 208 of the Federal Water Pollution Control Act Amendments of 1972 (PL 92-500). Section 208 required that regional plans be developed for coping with groundwater contamination in areas of industrialization and urbanization. The ISGS provided county-scale (Bogner 1976, Gilkeson and Westerman 1976, Larsen 1976, Specht and Westerman 1976, Stoffel and Larsen 1976, Taylor and Gilkeson 1977) and regional (Kempton et al. 1977) three-dimensional geologic maps and derivative maps of groundwater protection for the six-county Chicago metropolitan area.

In 1985, the Illinois Groundwater Protection Act (P.A. 85-863) was passed, mandating that groundwater resources and recharge areas be delineated and that aquifers be mapped. Further provisions stated a need to evaluate groundwater resources for every county and municipality in order for them to prepare a "groundwater protection needs assessment." The ISGS responded by preparing (1) a statewide map showing potential for aquifer recharge, which also depicts aquifer sensitivity (Keefer and Berg 1990), and (2) a case-study example explaining how such an assessment could be conducted using three-dimensional geologic information (Berg 1994). The ISGS also helped prepare an overall guidance document for conducting groundwater protection needs assessments (Cobb et al. 1995).

In the 1990s, the Illinois Department of Commerce and Community Affairs responded to the mandates of the Illinois Solid Waste Management Act and funded the ISGS County Assistance Program. The ISGS utilized its GIS to analyze natural resources, land use, and environmental impacts while providing technical assistance for siting regional pollution control facilities to counties requesting assistance. Using three-dimensional models of the geology, the ISGS specifically designed the program to delineate areas to avoid when siting solid waste disposal facilities for all or portions of Lake, Will, McLean, Carroll, Lee, and JoDaviess Counties (e.g., Riggs et al. 1993, Smith and McLean 1995, McGarry and Grimley 1997).

Depth to Aquifer and Aquifer Thickness

In Illinois, an aquifer's depth below the surface is a principal consideration in the evaluation of its contamination potential. The most common categories for depth to aquifer are these:

1. within 5 feet of the land surface
2. between 5 and 20 feet of the land surface
3. between 20 and 50 feet of the land surface
4. between 50 and 100 feet of the land surface
5. greater than 100 feet below the land surface

The depth-to-aquifer categories relate to historic practice. Cartwright and Sherman (1969) argued, and Illinois regulators proposed, that for the natural protection of groundwater, the base of a landfill should be separated from an aquifer by at least 30 feet of relatively impermeable material capable of attenuating contaminants. Aquifers within 50 feet of the land surface or 30 feet below the base of a typical landfill trench were mapped because landfill trench excavation to a maximum depth of 20 feet was a common practice. Therefore, in the 1970s and 1980s, evaluation of the upper 50 feet was considered to be most critical. In addition, Berg et al. (1984b) stated that the 20-foot depth was important because most land-use activity occurred within this interval and because the most accurate data were available for this depth interval.

However, by the late 1980s and throughout the 1990s, landfill trenches were commonly being excavated to depths >20 feet. In addition, studies of groundwater quality in the Midwest indicated that contamination from agricultural chemicals markedly decreased in water samples collected at a depth of >100 feet (Klaseus et al. 1989, Libra et al. 1993). Therefore, three-dimensional mapping and interpretations of aquifer sensitivity were extended to a depth of 100 feet (Curry et al. 1997, Berg and Abert 1999, Berg and Barnhardt 2000).

The depth category of <5 feet was introduced by Berg et al. (1984a,b) to obtain a finer differentiation of potential aquifer sensitivity from surface waste activities (e.g., septic leachate). This category is being maintained as a mapping convention for this Classification because data in the upper 5 feet are so easily attainable via interpretations of geologic parent materials from soil surveys. For example, sandy soils develop in sandy geologic materials when those sandy geologic materials are within 5 feet of the surface. Keefer (1995) showed that pesticide and nitrate leaching is enhanced in these sandy areas. This finding is particularly important in the glaciated portion of Illinois (about 75% of the state) where sand and gravel are frequently at the land surface.

Aquifer thickness categories of <20 feet, between 20 and 50 feet, and >50 feet (sometimes >100 feet) were selected because those categories were congruous with the depth-to-aquifer categories and they were also common, logical divisions in the distribution of aquifer thicknesses.

Stack-Unit Mapping

Compiling aquifer sensitivity maps requires being able to show subsurface geologic information on a flat map in an understandable format. A procedure called stack-unit mapping was first described by Kempton in Gross (1970) and further defined by Kempton (1981) and Kempton and Cartwright (1984). The earliest stack-unit map (to a depth of 20 feet) published in Illinois was by Hunt and Kempton (1977). Stack-unit mapping describes the distribution of all geologic materials in their order of occurrence from the land surface to a specified depth. Geologic materials that are aquifers, their depths, and thicknesses are clearly identified. To produce an aquifer sensitivity map, water-yielding and water-transmitting characteristics of materials within stacked sequences were determined, and the sequences were rated (from high to low) according to the sensitivity of aquifers within the sequence to become contaminated by potential waste sources. Stack-unit maps provided the necessary basic geologic information for development of aquifer sensitivity maps just prior to modern GIS and computer-mapping programs.

Aquifer Sensitivity Maps Based Primarily on Depth to Aquifer

Data from county stack-unit maps to a depth of 20 feet (Berg et al. 1984b) and statewide stack-unit maps to a depth of 50 feet (Berg and Kempton

1988) were used to develop, respectively, an aquifer sensitivity map for Boone and Winnebago Counties (Berg et al. 1984b) and a statewide aquifer sensitivity map (Berg and Kempton 1984). For both of these maps, stack units were interpreted and aquifers were differentiated according to aquifer type (sand and gravel vs. high-permeability bedrock) and depth beneath the surface. Relative aquifer sensitivity was rated based on aquifer depth within the upper 50 feet. Sand and gravel aquifers at the land surface were differentiated according to their thickness (e.g., <20 feet thick; >20 feet thick). The statewide sensitivity mapping added categories for cemented sandstone. In addition, both classifications considered the presence of discontinuous aquifers and uncertainty about the absence or presence of aquifers. Uncertainty arose as well-log data (showing the absence and presence of aquifer materials) were evaluated during construction of the maps. Logs showed conflicting descriptions from adjacent water-well boring logs where one log indicated buried sand and gravel and an adjacent log did not define the unit.

Advent of Computer Mapping and Three-Dimensional Geologic Modeling

With the advent of the modern GIS in the late 1980s and throughout the 1990s, it became possible to portray three-dimensional geology without first constructing a stack-unit map. Instead, software routines are used to create three-dimensional models of the subsurface based on information such as data showing the tops of successive layers and their thicknesses. For example, lithologic data showing the thickness and character of geologic materials have been entered into commercial-volume modeling software to produce three-dimensional geologic models (Berg and Abert 1994). Structure-contour (elevation) maps can then be made of the surface of buried units, and isopachous (thickness) maps can be made of any relevant units (e.g., Berg and Abert 1999). Depth-to-aquifer maps can be constructed for any desired depth by subtracting the elevation of the top surface of the aquifer from the land surface elevation (Soller et al. 1999).

Aquifer Thickness of Buried Units to Further Differentiate Sensitivity

Following three-dimensional mapping for part of Will County (Berg and Abert 1994) and for McHenry County (Berg 1994, Curry et al. 1997), the thickness of sand and gravel units was included as a ranking criterion. Aquifer sensitivity ratings were established recognizing that the thicker a sand and gravel unit, the more significant is its potential as a water resource, and the greater the need is to protect it. Thus, the ratings attempted to consider the magnitude of the impact of contaminated groundwater: thick aquifers have a greater potential to serve large populations than do thin aquifers.

Probability of Aquifer Occurrence to Further Differentiate Sensitivity

Soller and Berg (1992a,b) and Berg and Abert (1994) postulated that, as the thickness of surficial deposits increases, so does the probability of encountering a buried sand and gravel aquifer. This assumption is particularly important for areas underlain by non-aquifer bedrock materials (e.g., unfractured shale and unfractured limestones/dolomites). For example, regions lacking sand and gravel and having unfractured shale within 50 feet of the surface have a lower sensitivity than regions lacking sand and gravel and having unfractured shale between 50 and 100 feet of the surface. Invoking conservatism, the assumption states that areas mapped as "lacking sand and gravel" and underlain by unfractured shale or unfractured carbonate often are areas where data are lacking, and, therefore, those areas potentially contain an undiscovered sand and gravel groundwater resource. The thicker the drift, the higher the probability is that it contains an undiscovered sand and gravel aquifer.

Soil Data to Further Differentiate Sensitivity

Keefer (1995) conducted an exhaustive statewide analysis of how differences in soil associations (soil associations are generalizations of soil series, the basic soil map unit portrayed on county soil maps) and aquifer depths to 50 feet affect the potential

for contamination of aquifers by agricultural chemicals. Keefer designated nitrate and pesticide leaching classes of each soil series and association in Illinois and developed maps showing their leaching characteristics on a statewide basis. Leaching classes then were combined with depth-to-aquifer data to identify aquifer settings with similar water and transport characteristics and then ranked according to sensitivity for the entire state at a scale of 1:500,000.

Keefer's scheme is not considered in the following new classification of aquifer sensitivity categories because, when the hundreds of individual soils are combined with various depth-to-aquifer and aquifer thickness scenarios, thousands of possible combinations are created and an eventual aquifer sensitivity classification would be overly complex. However, when the production of aquifer sensitivity maps for agricultural chemicals for specific quadrangles is appropriate, combining the mapped soil series with sensitivity categories can be done easily (Berg and Abert 1999, Berg and Barnhardt 2000). This type of derivative map may be a useful addition for the many quadrangles containing extensive row-crop agriculture.

NEW CLASSIFICATION OF AQUIFER SENSITIVITY

The advent of new state- and federally funded 1:24,000-scale quadrangle mapping programs prompted pilot projects for three-dimensional geologic mapping and the development of aquifer sensitivity maps for the Villa Grove (Berg and Abert 1999) and Vincennes (Berg and Barnhardt 2000) Quadrangles. New funding also promised many geologic and aquifer sensitivity maps from other areas of the state; their production in the coming year is being planned. Therefore, a new classification was needed in light of the need to portray aquifer type, depth to aquifer, and aquifer thickness in an understandable and consistent format from map to map and in light of the large number of geologic and aquifer sensitivity maps that are planned for production in the coming years. The following scheme for rating aquifer sensitivity (see also fig. 1) was developed from the previous schemes developed since 1984. Generalizations, including some assumptions, were necessary to reduce the number of categories:

1. Aquifers are defined according to Section 620.210 of the Illinois Amendments to Groundwater Quality Standards (35 Ill. Adm. Code 620). The Code states that a potable ground water resource (e.g., an aquifer) can be found in a porous coarse-grained sand and gravel aquifer >5 feet thick, a high-permeability bedrock consisting of a porous sandstone aquifer >10 feet thick, and a porous and fractured limestone or dolomite aquifer >15 feet thick. This publication assumes that all mapped sand and gravel deposits, sandstones, and fractured carbonates are either aquifers or have the potential to be aquifers according to the definition.
2. Aquifer sensitivity classes are based on depth to the shallowest sand and gravel or bedrock aquifer. Depth-to-aquifer classes are 0 to 5 feet, 5 to 20 feet, 20 to 50 feet, 50 to 100 feet, and >100 feet.
3. There is no distinction between bedrock aquifers and sand and gravel aquifers or their resource potential, except as stated in Generalization 6. Hydraulic conductivity ranges are similar for sand and gravel, uncemented sandstone, and fractured limestone and dolomite (Table 1), except in karst areas where groundwater flow is often comparable with the flow rates of surface streams (Frankie et al. 1997) (see Generalization 10).
4. Thickness categories for sand and gravel and bedrock aquifers are <20 feet, 20 to 50 feet, and >50 feet.
5. Mappable aquifers are those with an areal extent of >0.063 square miles or 40 acres (i.e., they are a mappable deposit at 1:24,000 scale), which is equivalent to aquifer mapping that has been done at a scale of 1:500,000 where aquifers were mapped only when they were >1 square mile (640 acres) in size (Berg and Kempton 1988).
6. Cemented sandstone is considered low-yielding aquifer material as its hydraulic conduc-

Map Unit A1. Sand and gravel or high-permeability bedrock >50 feet thick within 5 feet of the land surface.[1]

Map Unit A2. Sand and gravel or high-permeability bedrock >50 feet thick between 5 and 20 feet below the land surface.

Map Unit A3. Sand and gravel or high-permeability bedrock 20 to 50 feet thick within 5 feet of the land surface.

Map Unit A4. Sand and gravel or high-permeability bedrock 20 to 50 feet thick between 5 and 20 feet below the land surface.

Map Unit A5. Cemented sandstone within 5 feet of the land surface.

Map Unit A6. Cemented sandstone between 5 and 20 feet below the land surface.

Map Unit B1. Sand and gravel or high-permeability bedrock between 5 and 20 feet thick within 5 feet of the land surface.[2]

Map Unit B2. Sand and gravel or high-permeability bedrock between 5 and 20 feet thick between 5 and 20 feet below the land surface.[2]

Map Unit B3. Discontinuous sand and gravel or high-permeability bedrock between 5 and 20 feet thick possibly present between 5 and 20 feet below the land surface.[2]

Map Unit C1. Sand and gravel or high-permeability bedrock >50 feet thick between 20 and 50 feet below the land surface.

Map Unit C2. Sand and gravel or high-permeability bedrock between 20 and 50 feet thick between 20 and 50 feet below the land surface.

Map Unit C3. Sand and gravel or high-permeability bedrock <20 feet thick between 20 and 50 feet below the land surface.[2]

Map Unit C4. Cemented sandstone between 20 and 50 feet below the land surface.

Map Unit C5. Discontinuous sand and gravel or high-permeability bedrock possibly present between 20 and 50 feet below the land surface.

Map Unit D1. Sand and gravel or high-permeability bedrock >50 feet thick between 50 and 100 feet below the land surface.

Map Unit D2. Sand and gravel or high-permeability bedrock between 20 and 50 feet thick between 50 and 100 feet below the land surface.

Map Unit D3. Sand and gravel or high-permeability bedrock <20 feet thick between 50 and 100 feet below the land surface.[2]

Map Unit D4. Cemented sandstone between 50 and 100 feet below the land surface.

Map Unit D5. Discontinuous sand and gravel or high-permeability bedrock may possibly be present between 50 and 100 feet below the land surface.

Figure 1 An aquifer sensitivity classification for Illinois.

Map Unit E1. Sand and gravel or high-permeability bedrock not present within 100 feet of the land surface.

Map Unit E2. Discontinuous sand and gravel possibly present within 100 feet of the land surface.

Map Unit F1. Between 50 and 100 feet of fine-grained unconsolidated material overlying unfractured shale or carbonate bedrock.

Map Unit F2. Between 20 and 50 feet of fine-grained unconsolidated material overlying unfractured shale or carbonate bedrock.

Map Unit F3. Less than 20 feet of fine-grained unconsolidated material overlying unfractured shale or carbonate bedrock.

Sand and gravel present at depths >100 feet in E area and below shallower sand and gravel in A, B, C, and D areas.[3]

Sandy tills at land surface.

Karst bedrock.

Disturbed land.

Surface water.

[1] High-permeability bedrock includes uncemented sandstone and fractured carbonates (limestone and dolomite).

[2] Sand and gravel must be >5 feet thick, uncemented sandstone >10 feet thick, and fractured carbonates >15 feet thick.

[3] Although sensitivity of deeper sand and gravel aquifers (may be >100 feet deep) is relatively low, the extent to which certain potentially detrimental land-use practices (e.g., hazardous waste sites) could adversely affect them is not known. Therefore, the overprint pattern showing their presence conservatively deals with the uncertainty. Bedrock aquifers at depths >100 feet are not accommodated because they are so widespread and continuous. An overprint pattern could cover an entire quadrangle and render aquifer sensitivity maps unnecessarily cluttered. The presence of deeper bedrock aquifers could be indicated by added map text.

tivity normally ranges from 1×10^{-7} to 1×10^{-4} cm/sec (Table 1); therefore, cemented sandstone was assigned a higher aquifer sensitivity than unfractured shale or unfractured limestone or dolomite. Several analyses for hydraulic conductivity of cemented sandstone were conducted by Battelle Memorial Institute and Hanson Engineers, Inc. (1992) as part of a site characterization program for a proposed low-level radioactive waste disposal facility in southern Illinois. Hydraulic conductivity varied from 5×10^{-6} to 2×10^{-2} cm/sec; most values were in the range of 4×10^{-5} to 9×10^{-4} cm/sec. Aquifer sensitivity categories for cemented sandstone are included within depth-to-aquifer categories (see map units A5, A6, C4, and D4).

7. Aquifers at or near the land surface are divided into two categories: those within 5 feet of the land surface and those 5 to 20 feet below the land surface (see map units A1 through A6, B1, and B2). This classification may be significant for evaluating the potential for contamination from land-use practices at the land surface (e.g., applications of agricultural chemicals) as opposed to those conducted deeper in the subsurface (e.g., landfilling of wastes).

8. Categories were added to accommodate discontinuous aquifers in the subsurface or uncertainty about the absence or presence of aquifers (see classes B3, C5, D5, and E2, which are shown as a diagonal overprint pattern on fig. 1). Because bedrock aquifers tend to be more uniform and widespread, this generalization mainly applies to subsurface discontinuous sand and gravel units.

9. An overprint pattern is used to show sandy tills (usually containing >40% sand) at the land surface. These tills do not offer much protection for underlying aquifers because they have a low clay content and often a frequent occurrence of sand and gravel lenses, are generally less than 20 feet thick, and are commonly weathered and fractured. However, their small percentage of clay and somewhat lower hydraulic conductivity (perhaps one or two orders of magnitude) than sand and gravel offer more aquifer protection than if sand and gravel were the only unit present at the land surface (Curry et al 1997). Although the occurrence of these sandy tills, without the presence of underlying sand and gravel, does not constitute an aquifer, the potential is slightly greater in these areas for downward migration of a contaminant, downslope flow along a contact with finer-grained materials, and discharge into a surface water body.

10. An overprint pattern is used (if desired) to depict sand and gravel aquifers (1) at depths of >100 feet in E areas and (2) below uppermost sand and gravel aquifers in A, B, C, and D areas. Although the potential to contaminate these deeper sand and gravel aquifers can be relatively low, the extent to which certain land-use practices (e.g., hazardous waste sites) could adversely affect the deeper resources is not known. Therefore, an overprint pattern showing the presence of these aquifers conservatively deals with the uncertainty. Bedrock aquifers at depths >100 feet are not accommodated in this classification per se because they are so widespread and continuous. Therefore, an overprint pattern for them could cover an entire 1:24,000-scale quadrangle and render aquifer sensitivity maps unnecessarily cluttered. The presence of deep bedrock aquifers could be indicated as a text notation on maps if desired.

11. An overprint pattern is used to show limestone and dolomite bedrock in karst terrains. In these areas, rocks have been dissolved by groundwater, resulting in sinkholes, caves, and underground streams. Karst areas are the most sensitive of any geologic setting because contaminants can be transported very rapidly. Karst terrains mostly occur where overlying fine-grained materials are <50 feet thick (Weibel and Panno 1997). Therefore, where present, they should be delineated in map units A and C (where limestone and dolomite is thick) and, to a lesser extent, map unit B (where rocks are thin).

12. Areas of disturbed land are shown by a gray pattern. Sensitivity may vary greatly depending on the degree of land modification and nature (if any) of fill materials.

13. Surface water is shown in blue. Lakes, rivers, and streams are usually discharge areas for groundwater. However, along some reaches of streams, surface water can recharge the uppermost aquifer. This type of recharge will most likely occur in map unit A.

Aquifer Sensitivity Map Units

Map units A to F are listed in order of decreasing sensitivity of aquifers becoming contaminated. Each of the twenty-four map units is described. Figure 1 shows corresponding colors to be used to designate the classes: red, orange, and yellow shades designate high to moderate aquifer sensitivities while green and blue shades designate moderately low to low aquifer sensitivities

Figure 1 also shows overprint patterns that may be used to show continuous and discontinuous occurrences of sand and gravel or high-permeability aquifers, some beneath shallow aquifers, in map units A, B, C, and D and to show the presence of any aquifers at a depth >100 feet in map unit E. Showing deeper aquifers is important when aquifer sensitivity maps are designed for use in siting hazardous or low-level radioactive waste disposal facilities or when map producers want to show the presence of the deeper aquifers. However, showing the presence of deeper bedrock aquifers must be carefully considered because such aquifers tend to be widespread, and, in many regions, their overprint pattern might clutter the maps. Another overprint pattern is used to show limestone and dolomite bedrock in karst terrains in map units A, B, and C.

Map Unit A: High Aquifer Sensitivity. Aquifer sensitivity is rated high where sand and gravel or highly permeable bedrock (including limestone and dolomite in karst terrains) is >20 feet thick and where it is within 20 feet from the surface. In these areas, contaminants from any source can move rapidly through porous media or fractures to drinking-water wells or nearby streams. Thick sand and gravel aquifers are also commonly connected to deeper subsurface sand and gravel aquifers, bedrock aquifers, or both (Berg 1994).

Map Unit A1. Sand and gravel or high-permeability bedrock >50 feet thick within 5 feet of the land surface.

Map Unit A2. Sand and gravel or high-permeability bedrock >50 feet thick between 5 and 20 feet below the land surface

Map Unit A3. Sand and gravel or high-permeability bedrock 20 to 50 feet thick within 5 feet of the land surface.

Map Unit A4. Sand and gravel or high-permeability bedrock 20 to 50 feet thick between 5 and 20 feet below the land surface.

Map Unit A5. Cemented sandstone within 5 feet of the land surface.

Map Unit A6. Cemented sandstone between 5 and 20 feet below the land surface.

Map Unit B: Moderately High Aquifer Sensitivity. Map unit B areas are characterized by sand and gravel or high-permeability bedrock (including limestone and dolomite in karst terrains) between 5 and 20 feet thick and within 20 feet of the land surface. Aquifers remain very sensitive in B areas because overlying fine-grained deposits are comparatively thin. Although groundwater in these deposits is rarely tapped for a groundwater resource, contaminated groundwater may flow into aquifers of adjoining units, or it could migrate along a contact of underlying fine-grained deposits and discharge onto slopes or into streams and lakes.

Map Unit B1. Sand and gravel or high-permeability bedrock between 5 and 20 feet thick (uncemented sandstone must be >10 feet thick and fractured carbonates >15 feet thick) within 5 feet of the land surface.

Map Unit B2. Sand and gravel or high-permeability bedrock between 5 and 20 feet thick (uncemented sandstone must be >10 feet thick and fractured carbonates >15 feet thick) between 5 and 20 feet below the land surface.

Map Unit B3. Discontinuous sand and gravel or high-permeability bedrock between 5 and 20 feet thick (uncemented sandstone must be >10 feet thick and fractured carbonates >15 feet thick) possibly present between 5 and 20 feet below the land surface.

Map Unit C: Moderate Aquifer Sensitivity. In areas of map unit C, sand and gravel or high-permeability bedrock (including limestone and dolomite in karst terrains) lies between 20 and 50 feet be-

low the land surface. Fine-grained materials overlying aquifers offer moderate protection from waste spreading, septic effluent, or application of agricultural chemicals.

Map Unit C1. Sand and gravel or high-permeability bedrock >50 feet thick between 20 and 50 feet below the land surface.

Map Unit C2. Sand and gravel or high-permeability bedrock between 20 and 50 feet thick between 20 and 50 feet below the land surface.

Map Unit C3. Sand and gravel or high-permeability bedrock <20 feet thick (sand and gravel must be >5 feet thick, uncemented sandstone >10 feet thick, and fractured carbonates >15 feet thick) between 20 and 50 feet below the land surface.

Map Unit C4. Cemented sandstone between 20 and 50 feet below the land surface.

Map Unit C5. Discontinuous sand and gravel or high-permeability bedrock possibly present between 20 and 50 feet below the land surface.

Map Unit D: Moderately Low Aquifer Sensitivity. Aquifer sensitivity is moderately low in areas where sand and gravel or high-permeability bedrock is between 50 and 100 feet below the land surface. Thick fine-grained materials should offer reasonable protection to aquifers from most contamination sources introduced at the land surface. However, although aquifer sensitivity is moderately low in D areas, aquifers can be as shallow as 50 feet, and, therefore, these areas are inappropriate for disposal of hazardous wastes or for the siting of a municipal landfill. Curry et al. (1997) cautioned that liquid wastes can migrate along cracks (e.g., from dessication) or other discontinuities that may extend as much as 50 feet below the land surface. Cracks in otherwise uniform fine-grained materials may increase the actual hydraulic conductivity by several orders of magnitude. For example, unfractured shale has a hydraulic conductivity range of 1×10^{-7} to 1×10^{-11} cm/sec, and fractured shale can have hydraulic conductivities exceeding 1×10^{-4}cm/sec (Table 1).

Map Unit D1. Sand and gravel or high-permeability bedrock >50 feet thick between 50 and 100 feet below the land surface.

Map Unit D2. Sand and gravel or high-permeability bedrock between 20 and 50 feet thick between 50 and 100 feet below the land surface.

Map Unit D3. Sand and gravel or high-permeability bedrock <20 feet thick (sand and gravel must be >5 feet thick, uncemented sandstone >10 feet thick, and fractured carbonates >15 feet thick) between 50 and 100 feet below the land surface.

Map Unit D4. Cemented sandstone between 50 and 100 feet below the land surface.

Map Unit D5. Discontinuous sand and gravel or high-permeability bedrock may possibly be present between 50 and 100 feet below the land surface.

Map Unit E: Low Aquifer Sensitivity. Areas mapped as unit E have an absence of sand and gravel aquifers and the presence of thick fine-grained deposits. However, for disposal of hazardous and low-level radioactive wastes, the presence of buried aquifers at a depth >100 feet must be considered (Berg et al. 1989; Killey and Berg, unpublished). Although the potential to contaminate aquifers may be low, it may still be politically unacceptable to dispose of these wastes above a known aquifer.

In addition, because of the lack of aquifers in E areas (F areas as well), rural home owners in many places must rely on large-diameter, shallow dug and bored wells for their water supply. These wells receive water from thin sand seams and fractures in till and rock. Studies (e.g., Schock et al. 1992) have shown that, because these wells are so shallow and have large openings to the surface, they have the highest frequency of occurrence of agricultural chemical contamination. Therefore, although aquifer sensitivity is low or nonexistent, groundwater contamination potential is quite high, and care must be taken to locate wells as far as possible from sources that can generate contaminants (e.g., septic systems, agricultural fields where agricultural chemicals have been applied, animal confinement areas).

Map Unit E1. Sand and gravel or high-permeability bedrock not present within 100 feet of the land surface.

Map Unit E2. Discontinuous sand and gravel possibly present within 100 feet of the land surface.

Map Unit F: Low Aquifer Sensitivity. Areas mapped as F contain unfractured shale or unfractured limestone/dolomite bedrock within 100 feet of the land surface, and there is a high probability that sand and gravel aquifers are absent. However, areas mapped as lacking sand and gravel may also be areas for which data are lacking. To be conservative, this rating scheme considers the possibility that undiscovered sand and gravel resources may be present. Therefore, sensitivity classes F1 to F3 show the potential for the presence of sand and gravel aquifers to decrease as the thickness of fine-grained unconsolidated glacial deposits decreases. The discovery of any discontinuous aquifers would automatically reclassify F areas as B3, C5, or D5.

Map Unit F1. Between 50 and 100 feet of fine-grained unconsolidated material overlying unfractured shale or unfractured limestone/dolomite bedrock.

Map Unit F2. Between 20 and 50 feet of fine-grained unconsolidated material overlying unfractured shale or unfractured limestone/dolomite bedrock.

Map Unit F3. Fewer than 20 feet of fine-grained unconsolidated material overlying unfractured shale or unfractured limestone/dolomite bedrock.

CONCLUSIONS

This new aquifer sensitivity classification scheme provides map producers and users with a way to assess, rate, and portray aquifer sensitivity classes throughout the state. The classification scheme is adaptable for showing the presence of buried aquifers at depths >100 feet. The scheme also makes it easy to add sensitivity classes below the 100-foot depth (i.e., to assess sensitivity of aquifers at depths of 150, 200, 250, and 300 feet, and deeper). For example, if geologic mapping discovered a buried sand and gravel aquifer within a unit E area at a depth of 240 feet, the mapper has two options: (1) to use the sand and gravel overprint pattern to indicate the presence of an aquifer below the 100-foot depth, or (2) to create new categories such that the "new E" indicates an aquifer between 100 and 150 feet of the land surface, the "new F" indicates an aquifer between 150 and 200 feet of the land surface, and the "new G" indicates an aquifer between 200 and 250 feet. A new category "H" would replace the current F category as the least sensitive map area.

Aquifer sensitivity maps will be among the most important derivative products from the Illinois program of three-dimensional geologic mapping at 1:24,000 scale. The approach discussed in this report should simplify the map production process, result in map products that interpret the geology in a consistent manner for aquifer sensitivity, and provide map users with more easily understood aquifer sensitivity maps that are consistent, regardless of location and scale within the state of Illinois.

This classification is dependent on (1) geologic information that is relatively easy to obtain while conducting a three-dimensional geologic mapping program (aquifer type, depth to the uppermost aquifer, and aquifer thickness), (2) assignment of surrogate hydrogeologic characteristics to the mapped geologic materials, and (3) interpretation of the three-dimensional geology according to basic aquifer sensitivity rules. Development of new technologies and methods for determining hydrologic and hydraulic properties of materials is strongly encouraged so that new ways to portray aquifer sensitivity in greater detail are possible. The integration of additional hydraulic and hydrologic data with the new scheme will enhance the sensitivity assessments.

REFERENCES

Battelle Memorial Institute and Hanson Engineers, Inc., 1992, Geff Alternative Site: Wayne County, Illinois, Data Report, v. II.

Berg, R.C., 1994, Geologic aspects of a groundwater protection needs assessment: Illinois State Geological Survey Environmental Geology 146, 27 p.

Berg, R.C., and C.C. Abert, 1994, Large-scale aquifer sensitivity model: Environmental Geology, v. 24, no. 1, p. 24–42.

______, 1999, General aquifer sensitivity map, Villa Grove Quadrangle, Douglas County, Illinois, Illinois State Geological Survey Geologic Quadrangle map: IGQ Villa Grove-AS, scale 1:24,000.

Berg, R.C., and M.L. Barnhardt, 2000, General aquifer sensitivity map, Vincennes Quadrangle, Indiana and Illinois, Illinois State Geological Survey Geologic Quadrangle map: IGQ Vincennes-AS, scale 1:24,000.

Berg, R.C., and J.P. Kempton, 1984, Potential for contamination of shallow aquifers from land burial of wastes: Illinois State Geological Survey map, in color, scale 1:500,000.

———, 1988, Stack-unit mapping of geologic materials in Illinois to a depth of 15 meters: Illinois State Geological Survey Circular 542, 23 p.

Berg, R.C., J.P. Kempton, and K. Cartwright, 1984a, Potential for contamination of shallow aquifers in Illinois: Illinois State Geological Survey Circular 532, 30 p.

Berg, R.C., J.P. Kempton, and A.N. Stecyk, 1984b, Geology for planning in Boone and Winnebago Counties, Illinois: Illinois State Geological Survey Circular 531, 69 p.

Berg, R.C., H.A. Wehrmann, and J.M. Shafer, 1989, Geological and hydrological factors for siting hazardous or low-level radioactive waster disposal facilities: Illinois State Geological Survey Circular 546, 61 p.

Bogner, J.E., 1976, Geology for planning in northeastern Illinois. V. Geology for planning in Cook County: Illinois State Geological Survey Open File Series 1976-5, 32 p.

Cartwright, K., and B.R. Hensel, 1993, Hydrogeology, *in* D.E. Daniel, ed., Geotechnical Practice for Waste Disposal: New York, Chapman and Hall.

Cartwright, K., and F.B. Sherman, 1969, Evaluating sanitary landfill sites in Illinois: Illinois Environmental Geology Notes, v. 27, 25 p.

Cobb, R.P., R.C. Berg, and H.A. Wehrmann, 1995, Guidance document for groundwater protection needs assessments: Illinois Environmental Protection Agency, Public Water Supplies, IEPA/PWS95-01, 98 p.

Curry, B.B., R.C. Berg, and R.C. Vaiden, 1997, Geologic mapping for environmental planning, McHenry County, Illinois: Illinois State Geological Survey Circular 559, 79 p.

Frankie, W.T., D.A. Grimley, R.J. Jacobson, R.D. Norby, S.V. Panno, M.A. Phillips, J.E. Hofmann, and M.R. Jeffords, 1997, Guide to the geology of the Columbia and Waterloo area, Monroe County, Illinois: Illinois State Geological Survey Field Trip Guidebook 1997A, April 19, 1997, 99 p.

Gilkeson, R.H., and A.A. Westerman, 1976, Geology for planning in northeastern Illinois, II, Geology for planning in Kane County: Illinois State Geological Survey Open File Series 1976-2, 39 p.

Gross, D.L., 1970, Geology for planning in DeKalb County, Illinois: Illinois State Geological Survey Environmental Geology Notes, v. 33, 26 p.

Hackett, J.E., 1963, Ground-water contamination in an urban environment: Program with abstracts 1963 Annual Meeting Geological Society of America, p. 70A–71A.

———, 1965, Groundwater contamination in an urban environment: Groundwater, v. 3 no. 3, p. 27–30.

Hunt C.S., and J.P. Kempton, 1977, Geology for planning in DeWitt County, Illinois: Illinois State Geological Survey Environmental Geology Notes, v. 83, 42 p.

Illinois State Geological Survey, 1999, Geology—Foundation for the new century: Illinois State Geological Survey Annual Report, 77 p.

Keefer, D.A., 1995, Potential for agricultural contamination of aquifers in Illinois: 1995 revision: Illinois State Geological Survey Environmental Geology 148, 28 p.

Keefer, D.A., and R.C. Berg, 1990, Potential for aquifer recharge in Illinois: Illinois State Geological Survey Map.

Kempton, J.P., 1981, Three-dimensional geologic mapping for environmental studies in Illinois: Illinois State Geological Survey Environmental Geology Notes 100, 41 p.

Kempton, J.P., R.C. Berg, and D.R. Soller, 1989, Hydrogeological application to regional three-dimensional lithostratigraphic mapping: Memoires for the International Symposium of Hydrogeologic Maps as Tools for Economic and Social Development, Hanover, Federal Republic of Germany, p. 423–426.

Kempton, J.P., J.E. Bogner, and K. Cartwright, 1977, Geology for planning in northeastern Illinois, VIII, Regional summary: Illinois State Geological Survey Open File Series 1977-2, 84 p.

Kempton, J.P., and K. Cartwright, 1984, Three-dimensional geologic mapping; A basis for hydrogeologic and land-use evaluations: Bulletin of the Association of Engineering Geologists, v. 21, no. 3, p. 317–335.

Klaseus, T.G., G.C. Buzicky, and E.C. Schneider, 1989, Pesticides and groundwater: Surveys of selected Minnesota wells: Minnesota Department of Public Health and Minnesota Department of Agriculture, 95 p.

Larsen, J.I., 1976, Geology for planning in northeastern Illinois, VI, Geology for planning in Will County: Illinois State Geological Survey Open File Series 1976-6, 35 p.

Libra, R.D., G.R. Hallberg, K.D. Rex, B.C. Kross, L.S. Siegley, M.A. Kulp, R.W. Field, D.J. Quade, M. Selim, B.K. Nations, H.H. Hall, L.A. Etre, J.K. Johnson, H.F. Nicholson, S.L. Berberich, and K.L Cherryholmes, 1993, The Iowa state-wide rural well-water survey: June 1991, repeat sampling of the 10% subset: Iowa Department of Natural Resources Technical Information Series 26, 30 p.

McGarry, C.S., and D.A. Grimley, 1997, Aquifer sensitivity of Carroll County, Illinois: Illinois State Geological Survey Open File Series 1997-13i, Map, scale 1:62,500.

Riggs, M.H., C.C. Abert, M.M. McLean, R.J. Krumm, and E.D. McKay, 1993, Cumulative sand and gravel thickness, north-central Lake County: Illinois State Geological Survey Open File Series 1993-10f, Map, scale 1:62,500.

Schock, S.C., E. Mehnert, M.E. Caughey, G.B. Dreher, W.S. Dey, S. Wilson, C. Ray, S.-F.J. Chou, J. Valkenburg, J.M. Gosar, J.R. Karny, and M.L. Barnhardt, 1992, Pilot study: Agricultural chemicals in rural, private wells in Illinois: Illinois State Water Survey and Illinois State Geological Survey, Cooperative Ground-water Report 14, 80 p.

Sheaffer, J.R., B. Von Boehm, and J.E. Hackett, 1963, Refuse disposal needs and practices in northeastern Illinois: Northeastern Illinois Planning Commission Technical Report 3, 72 p.

Smith E.C., and M.M. McLean, 1995, Upper sand and gravel isopach in Will and southern Cook Counties, Illinois: Illinois State Geological Survey Open File Series 1995-13d, Map, scale 1:100,000.

Soller, D.R., and R.C. Berg, 1992a, A model for the assessment of aquifer contamination potential based on regional geologic framework: Environmental Geology and the Water Sciences, v. 19, no. 3, p. 205–213.

———, 1992b, Using regional geologic information to assess relative aquifer contamination potential—An example from the central United States: U.S. Geological Survey Open File Report 92-694, Map, scale 1:100,000 with text.

Soller, D.R., S.D. Price, J.P. Kempton, and R.C. Berg, 1999, Three-dimensional geological maps of Quaternary sediments in east-central Illinois: USGS I-map 2669, three atlas sheets.

Specht, S.A., and A.A. Westerman, 1976, Geology for planning in northeastern Illinois, III, Geology for planning in McHenry County: Illinois State Geological Survey Open File Series 1976-3, 39 p.

Stoffel, K.L., and J.I. Larsen, 1976, Geology for planning in northeastern Illinois, IV, Geology for planning in Lake County: Illinois State Geological Survey Open File Series 1976-4, 33 p.

Taylor, S.M., and R.H. Gilkeson, 1977, Geology for planning in northeastern Illinois, VII, Geology for planning in DuPage County: Illinois State Geological Survey Open File Series 1977-2, 31 p.

U.S. Environmental Protection Agency, 1993, Ground water resource assessment: Office of Water 4602, EPA 813-R-93-003, 232 p.

U.S. Geological Survey, 1999, Sustainable growth in America'a heartland— 3-D geologic maps as a foundation: U.S. Geological Survey Circular 1190, 17p.

Weibel, C.P., and S.V. Panno, 1997, Karst terrains and carbonate rocks in Illinois: Illinois State Geological Survey Illinois Map 8, scale 1:500,000.